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Measurement of surface resistance of silicone rubber sheets under polluted and dry band conditions

Arshad¹ · A. Nekahi¹ · S. G. McMeekin¹ · M. Farzaneh²

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Abstract Ageing and degradation of silicone rubber insulators in contaminated environments is a major concern due to their organic nature. Understanding the flashover process of silicone rubber insulators under contamination is very important and needs standardized tests and procedures. Surface resistance measurement can be used as an indication of ageing and contamination severity of outdoor silicone rubber insulators. This paper presents experimental and mathematical results on surface resistance of high-temperature vulcanized silicone rubber sheets under various environmental and contaminated conditions. Rectangular silicone rubber sheets were polluted artificially in laboratory using a modified solid layer method based on IEC 60507 and tested in a climate chamber where fog rate, humidity and temperature can be controlled. Influence of non-soluble salt deposit density (NSDD), pollution severity, relative humidity, ambient temperature, dry band location and width, and multiple dry bands on surface resistance have been investigated. The obtained results show that surface resistance decreases with increase in NSDD, pollution severity and relative humidity. Increase in surface resistance was observed with the formation of dry bands. Although surface resistance was effected by all parameters, the most dominant parameter was noted

down to be pollution severity level and dry band formation. Repeatability of results was confirmed by performing each test five times and concluded that surface resistance measurement can be standardized to evaluate ageing and pollution severity of silicone rubber insulators. These results along with the available literature on equivalent salt deposit density (ESDD) measurement could be used to formulate a relation between ESDD and surface resistance that could be useful for evaluating the performance of silicone rubber insulators in wet and contaminated environments.

Keywords Silicone rubber · Pollution · Ambient temperature · Relative humidity · NSDD · ESDD · Dry bands · Surface resistance

1 Introduction

Outdoor insulators used in transmission and distribution systems are exposed to various types of stresses during service conditions electrical, mechanical and environmental [1]. The design and selection of outdoor insulators are largely dependent on their performance under contaminated and humid conditions. The reliability of power transmission and distribution system is dependent on the performance of outdoor insulators.

Under dry conditions, contamination has little effect on flashover process, but under moisture, cold fog or rain the soluble contaminant dissolves in water leading to the flow of leakage current along the insulator surface [2,3]. The non-uniform pollution distribution along the insulator surface leads to non-uniform current density. The non-uniformity of leakage current flow results in heating and dry band formation. When the voltage drop along the dry band exceeds the

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withstand capability of the dry band, an arc is initiated which may lead to flashover under certain conditions.

Silicone rubber has been used extensively for outdoor insulation in the last few decades. The low surface energy of silicone rubber materials inhibits the formation of continuous wet layer on their surface resulting in isolated water droplets [4]. Silicone rubber offers many advantages as compared to porcelain and glass insulators due to their superior property of hydrophobicity. The better flashover performance of silicone rubber insulators is due to their resistance to the formation of a uniform water layer that leads to reduction in leakage current flow and high surface resistance [5–7]. Although silicone rubber materials offer many advantages, they are also vulnerable to ageing and degradation due to their organic nature. Under wet and contaminated conditions, discrete water droplets form on the surface of silicone rubber insulators. Numerical simulations of electric field distributions revealed that the electric field intensity is high at the junction of water droplet, air and insulator surface [8,9]. High electric field stress at the edge of water droplets leads to corona and partial arcs. These partial arcs and discharges lead to reduction of surface hydrophobicity and surface resistance which may lead to flashover.

Equivalent salt deposit density (ESDD) is used to predict flashover voltage and contamination severity of outdoor insulators [10]. For silicone rubber insulators, the flashover process and pollution deposition are completely different than that of porcelain and glass insulators, and therefore, ESDD alone cannot be used to predict flashover voltage and contamination severity [7,11].

Furthermore, silicone rubber materials are subjected to ageing and degradation in contaminated environments. Ageing of silicone rubber insulators is a complex phenomenon and dependent on various parameters like pollution severity, housing material and other environmental conditions. Ageing of outdoor insulators cannot be predicted by measuring ESDD, and therefore, an alternate solution is required. The IEEE task force report on insulator contamination proposed that surface resistance can be used for quantifying the ageing and contamination severity of polymeric insulators [12]. They also presented guidelines on how to measure the surface resistance of polymeric insulators under contaminated conditions.

Apart from pollution severity, surface resistance of silicone rubber insulators is influenced by many other parameters. The results presented in [13] show that surface resistance is dependent on contamination level and wetting mode. Similarly, it was reported in [14] that heat treatment of silicone rubber material also decreases its surface resistivity in clean conditions. The results presented in [3] show that silicone rubber has the ability to interact with pollutants and reduce the conductivity of the pollution layer leading to high surface resistance. This property of silicone rubber material makes

the process of ageing and contamination more complex. The previous literature on the measurement of surface resistance considered only contamination severity [3, 12–16]. However, according to the authors' knowledge surface resistance may also be affected by pollution material, environmental condition and pollution distribution on the insulator surface. There is very limited literature available on the influence of inert pollution material, humidity, temperature and dry band formation on surface resistance of silicone rubber materials.

Unlike porcelain and glass insulators, flashover of silicone rubber insulators may not be accurately predicted by measuring the ESDD only. It is believed that measuring surface resistance of silicone rubber insulators under contaminated conditions may be helpful in predicting the ageing and contamination severity accurately. This paper uses the guidelines presented in [12] to thoroughly investigate the effect of different environmental and polluted conditions on surface resistance of silicone rubber sheets. A total of seven parameters were chosen for this investigation: pollution severity, non-soluble salt deposit density (NSDD), relative humidity, ambient temperature, dry band location, dry band width and multiple dry bands. The influence of these parameters on the surface resistance of silicone rubber sheets was thoroughly investigated in laboratory. These results could be useful in insulator design and selection for contaminated environments and may also be used for better understanding the flashover process of polluted silicone rubber insulators.

2 Mathematical models of surface resistance

Efforts have been done in the past to develop mathematical models for calculating surface resistance under contaminated conditions. For a cylindrical insulator having diameter d which is equal to the mean of shed and sheath region, surface resistance is modelled using the following equations [17].

$$\text{Surface Resistance} = \frac{4L}{\sigma \pi ((t + d)^2 - d^2)}$$

where d is the insulator diameter, t is the thickness of degraded insulator layer, L is the insulator length and σ is the pollution layer conductivity. This model can be used to calculate the surface resistance for degraded insulators. Using the above model, it was concluded that for a completely hydrophilic surface, the flashover will occur if the degraded layer thickness is greater than 40 μm . The limitation of this model is the assumption of a completely wettable surface which is seldom the case in silicone rubber insulators.

Another mathematical model for surface resistance calculation was presented in [3] for a disc-like pollution layer of polymer insulators. This model assumes that the arc is in contact with a very small region of the pollution layer and only

a quadrant of pollution layer is considered for calculations. The contamination layer considered here is represented by a curved region of thickness t , inner radius a , outer radius b and resistivity ρ . The potential at the inner and outer radius is assumed to be zero and V_o , respectively. The potential difference along a curved region is given by the following equation.

$$V = \frac{V_o}{\ln \frac{b}{a}} \ln \frac{\rho}{a} \quad (1)$$

From Maxwell's equation, it can be derived that

$$E = -\nabla V = -\frac{V_o}{\rho \ln \left(\frac{b}{a}\right) a} \quad (2)$$

$$J = \sigma E \quad (3)$$

$$I = \int J dA = \int_{\theta=0}^{\frac{\pi}{2}} \int_{t=0}^t \frac{\sigma V_o}{\rho \ln \left(\frac{b}{a}\right)} \rho dz d\theta \quad (4)$$

$$I = \frac{\pi}{2} \frac{t V_o \sigma}{\ln \left(\frac{b}{a}\right)} \quad (5)$$

$$\text{Surface Resistance} = \frac{V_o}{I} = \frac{2 \ln \frac{b}{a}}{\sigma \pi t} \quad (6)$$

The above model assumes that the insulator surface is uniformly polluted and the pollution layer thickness is constant. However, for hydrophobic insulators, the insulator interacts with the pollution constituents and getting a uniform pollution layer is seldom the case. Furthermore, in field conditions, the pollution distribution along the insulator surface may not be uniform and depend on various parameters, e.g. wind speed, direction, insulator geometry and orientation. In this paper, an attempt has been made to experimentally investigate the surface resistance of silicone rubber surfaces which can be used to extend the applicability of existing mathematical models.

3 Sample preparations

Rectangular samples of silicone rubber obtained from provincial rubber (GP70THT) having temperature range of 60–300 °C and dimensions of $10 \times 4 \times 0.6 \text{ cm}^3$ were used for the tests. The thermal conductivity, dielectric constant and dissipation factor were $0.24 \text{ W m}^{-1} \text{ K}^{-1}$, 2.9 and 3×10^{-4} , respectively. The modified solid layer method based on IEC 60507 was used for polluting the samples. The modified solid layer method [18] involves pre-conditioning of the insulator surface with dry kaolin to suppress the surface hydrophobicity. After pre-conditioning with dry kaolin, all samples are checked by wettability class to see whether the samples are hydrophilic. Triton X-100 is used in the pollution suspension as a wetting agent which help in the application of uniform

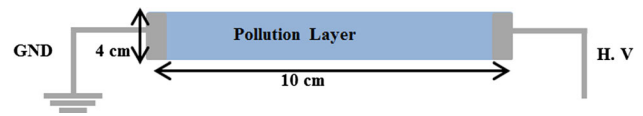


Fig. 1 Test sample showing electrode set-up and sample dimensions

pollution layer. A pollution suspension consisting of 40-g kaolin, 1 g of Triton X-100 and appropriate amount of NaCl (depending on conductivity of suspension) is prepared and applied to the samples. Conductivity of the pollution suspension is varied to prepare samples with light, medium, heavy and very heavy pollution severity level [19]. To prepare samples with different NSDD level, the amount of NaCl is kept constant, while concentration of kaolin is varied to prepare samples with 0.1, 0.3, 0.5 and 0.75 mg/cm^2 NSDD values. Clean bands of 1 cm width are created near the high-voltage electrode, grounded electrode and middle part of the samples. Similarly, for dry band width experiments, dry bands of 0.5, 1.0, 1.5 and 2.0 cm are created near the high-voltage electrode. Samples with 2 and 3 dry bands were also prepared to study the influence of multiple dry bands on surface resistance. Figure 1 shows the basic structure and dimensions of silicone rubber sample. Different sample configurations used for tests are shown in Fig. 2. Clean bands of different widths were created at grounded, middle part and high-voltage end to study the dry band conditions.

4 Experimental set-up

Figure 3 shows a simplified test set-up used for experiments. An insulated stand made of acrylic glass was used for placing the silicone rubber sample. The samples were placed in a climate chamber having dimensions of $2.5 \text{ m} \times 2.5 \text{ m} \times 2.0 \text{ m}$. The climate chamber is equipped with sensors and nebulizers to control temperature, humidity and fog rate inside the chamber. During the experiments, fog rate was kept constant at 4 l/h, while relative humidity and temperature were varied. Relative humidity can be increased easily inside the chamber, but it was challenging to decrease the humidity because of the high atmospheric humidity. Therefore, a dehumidifier was used to decrease relative humidity inside the room and climate chamber. A high-voltage system of 0–100 kV and 50 Hz was used to energize the samples. Two copper plates of 1 cm width were used as high-voltage and grounded electrodes. The electrodes were attached to the sample surface using copper screws. Voltage was measured using a capacitive voltage divider. Leakage current was measured using a current transformer (Bergoz Instrument) connected to an NI data acquisition card (NI USB-6003). NI USB-6003 is 16-bit resolution device having 8 analogue inputs and two outputs and 13 digital I/O lines with sampling frequency of 100 kS/s.

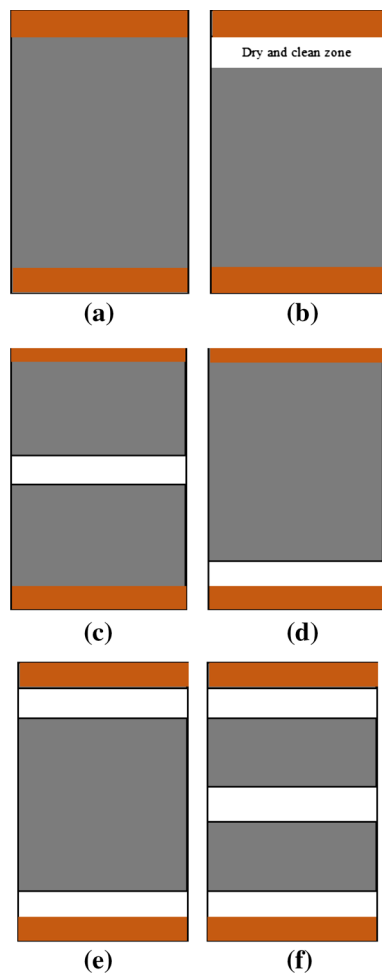


Fig. 2 Test samples: **a** uniform pollution, **b** dry band at HV end, **c** dry band at middle part, **d** dry band at ground end, **e** two dry bands, **f** three dry bands

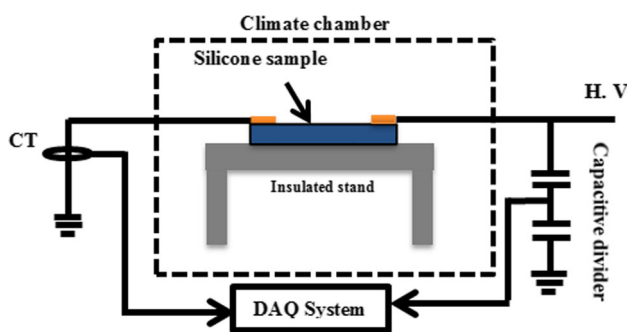


Fig. 3 Test set-up

The DAQ card was connected to a desktop PC through a USB cable. Two channels were used for acquiring voltage and leakage current signals in the continuous acquisition mode. The acquired leakage current and voltage waveforms were stored in .csv file format for post processing.

5 Test method

Rectangular silicone rubber samples were polluted artificially in the laboratory and dried in open air for 24 h before performing the tests. For surface resistance measurements, the guidelines provided by IEEE task force on insulator contamination [12] were closely followed. The applied voltage was chosen to be 15 V/mm for configurations (a)–(d), while 20 V/mm was used for configurations (e)–(f). The leakage current recorded in configurations (e)–(f) was not enough for surface resistance measurement; therefore, the applied voltage was increased to 20 V/mm. The samples were stressed for 1 h, and leakage current was recorded using the current transformer under clean fog conditions. Each test was repeated five times, and pollution was reapplied after every test. Tests were conducted under different climate conditions. Fog was generated in the climate chamber with a moderate rate of 4 l/h in all tests. Relative humidity and ambient temperature were varied to study their effect on surface resistance. After surface resistance measurement, voltage was increased in steps of 5% of the predicted flashover voltage to measure arc inception and flashover voltages.

6 Experimental results

Performance of outdoor insulators in humid and contaminated conditions plays an important role in the reliable transmission of power. Outdoor insulators are vulnerable to surface flashovers under moist and contaminated conditions. ESDD measurement has been standardized to predict the surface contamination of outdoor ceramic and porcelain insulators. However, due to the low surface energy of silicone rubber materials, ESDD method may not produce accurate results [12]. So far, there is no international standard to predict the contamination severity of silicone rubber and other polymeric insulators. Surface resistance of outdoor insulators plays a vital role in determining the flashover strength. In the case of clean and dry insulators, surface resistance is very high and only a few microamperes current can flow through the insulator under high-voltage stress. Under wet and contaminated conditions, pollution layer conductivity increases and leads to lower surface resistance. To predict the flashover voltage of silicone rubber insulators, it is better to consider surface resistance along with ESDD for reliable results. In this section, surface resistance of silicone rubber sheets was measured under different ESDD, humidity and dry band conditions. Figure 4 shows surface resistance of a medium polluted silicone rubber sheets. As shown in Fig. 4, surface resistance is high initially and decreases as the test time increases because of the increase wetting and formation of relatively uniform water layer on the insulator surface. However, after 30–40 min a steady-state value of surface

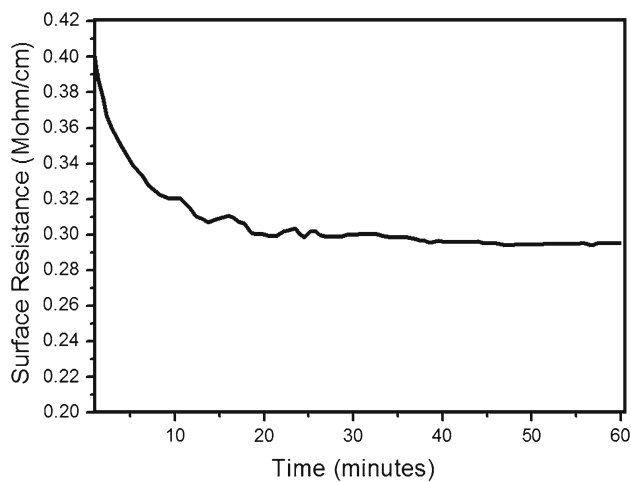


Fig. 4 Change in surface resistance with time: medium pollution severity, moderate humidity, 10 °C temperature, NSDD = 0.75 mg/cm², standard deviation = 2.8%

resistance was obtained which remained constant for the rest of the test duration. Test was interrupted after 60 min, and it is assumed that the surface resistance value will remain constant even if the test is performed for longer duration. The results presented in Fig. 4 are the average values of 5 tests, and the standard deviation was found to be 2.8%. This might be due to the manual application of pollution layer, difference in surface conditions after pre-conditioning (wettability class) and wetting rate [19].

6.1 Influence of pollution severity

Flashovers of outdoor insulators due to contamination build up results in power outages and significant economic loss. Predicting flashover of outdoor insulators in contaminated environments is very important for reliable operation of power systems. Previous studies have considered ESDD for predicting the flashover of outdoor insulators [10,20]. Due to the hydrophobic nature of silicone rubber insulators, however, ESDD is considered insufficient for accurately predicting flashover voltage and ageing [7,21]. In this section surface resistance of rectangular silicone rubber sheets was measured under different contamination conditions. Tests were conducted on four different sample having light, medium, heavy and very heavy pollution severity. Fog rate, relative humidity and temperature were kept constant inside the climate chamber. The amount of non-soluble deposit in the pollution slurry was also constant at 0.75 mg/cm², while the amount of soluble contaminant (NaCl) was varied to obtain volume conductivities of 1.4, 4, 8 and 16 S/m. Each sample was used once for the test, and pollution was reapplied after test to make sure that the pollution layer is uniform. Figure 5 shows average values of surface resistance obtained at different pollution severity levels. In the case of light pol-

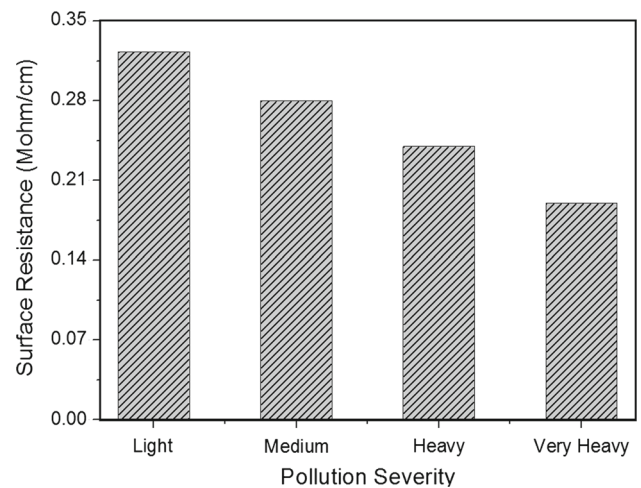


Fig. 5 Variation in surface resistance with pollution severity: NSDD = 0.75 mg/cm², temperature = 10 °C, moderate humidity, standard deviation = 2.8–4.3%

lution, surface resistance value was noted to be 0.32 MΩ/cm and reduce to 0.19 MΩ/cm for very heavy pollution severity level. The minimum value of surface resistance that can cause flashover for silicone rubber insulator is reported to be 0.142 MΩ/cm [15] below which the probability of flashover is high. In this case, it can be observed that even at the case of very heavy pollution severity, surface resistance is higher than the critical value and flashover may not occur unless silicone rubber lose its hydrophobicity. It can be seen from Fig. 5 that change in pollution severity significantly changes surface resistance of silicone rubber insulators.

6.2 Influence of NSDD

Inert pollution material influences the flashover process of ceramic and polymeric insulators in wet environments and has been reported in [22,23]. In the case of silicone rubber insulators, the effect of inert material on flashover processes is associated with hydrophobicity loss and recovery [24]. In this section, experiments were carried out to study the effect of NSDD on surface resistance of silicone rubber sheets. Four samples were prepared for each test with volume conductivity of 1.4 S/m, while the amount of kaolin was varied to prepare pollution slurry with NSDD of 0.1, 0.3, 0.5 and 0.75 mg/cm². Similar procedure was repeated for medium, heavy and very heavy pollution severity. Fog rate, relative humidity and ambient temperature were kept constant in the climate chamber at 4 l/h, 80% and 10 °C, respectively. Each test was repeated 5 times, and average values are presented here. From experimental results, it was observed that surface resistance is high initially and varies frequently, but after 30–40 min of high-voltage stress, a steady-state value of surface resistance sets in. For a constant volume conductivity, surface resistance decreased with increased in NSDD as shown

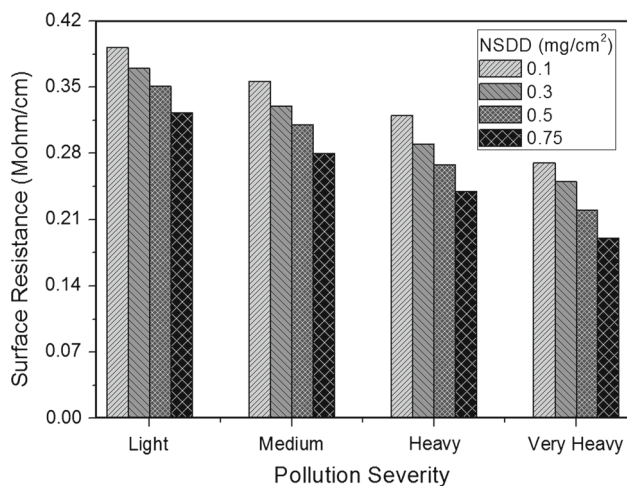


Fig. 6 Variation in surface resistance with NSDD: uniform pollution, moderate humidity, temperature = 10 °C, standard deviation = 1.8–4.6%

in Fig. 6. With increase in NSDD value, surface resistance decreased which might be because of the uniformity of the pollution layer with higher NSDD values [25]. Higher NSDD values also slow down the hydrophobicity recovery leading to uniform water layer at the insulator surface, which in turn decrease surface resistance and flashover voltage. Figure 6 shows surface resistance of silicone rubber insulators at different NSDD values. The standard deviation was found to be between 1.8 and 4.6% in all tests which might be due to the changes in fog rate, surface hydrophobicity and pollution layer [25].

6.3 Influence of relative humidity

The previous literature shows that surface resistance of porcelain and glass insulators is dependent on relative humidity along with other parameters. It was reported in [26] that surface resistance decreases five times with increase in humidity from 40 to 100%. This behaviour is different for silicone rubber insulators due to their surface hydrophobicity. Experiments were carried out at three different humidity levels to study the surface resistance of silicone rubber samples where low humidity corresponds to 40–60%, moderate 60–80% and high humidity 80–100%. A dehumidifier was used to decrease humidity inside the climate chamber. Ambient temperature and fog rate was kept constant, while volume conductivities of samples were changed to model light, medium, heavy and very heavy pollution. At high humidity level, a sudden decrease in surface resistance was observed after complete wetting of the surface. With increase in relative humidity, the moisture present in the surrounding air absorbs on the insulator surface leading to increase in leakage current and subsequent decrease in surface resistance and flashover voltage. Furthermore, the effect of increased

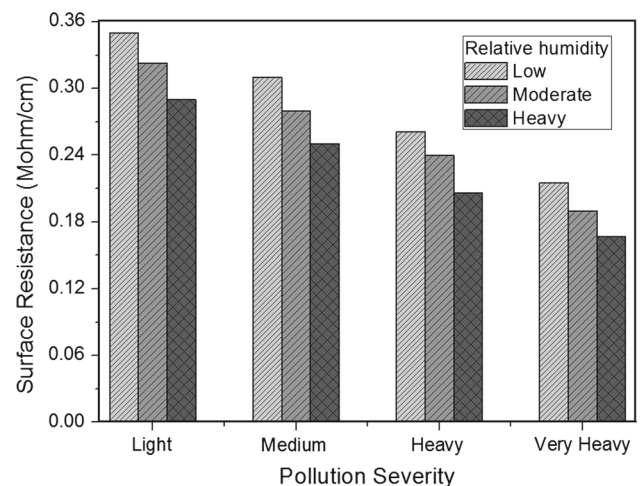


Fig. 7 Variation in surface resistance with relative humidity: uniform pollution distribution, NSDD = 0.75 mg/cm², temperature = 10 °C, standard deviation = 3.1–4.6%

relative humidity was more evident for very heavy pollution as compared to light and medium pollution severity level as shown in Fig. 7.

6.4 Influence of ambient temperature

Ambient temperatures influence the performance of outdoor insulators in many different ways. The results presented in [27] showed that hydrophobicity recovery of silicone rubber is dependent on ambient temperature. A decrease in hydrophobicity recovery along with a decrease in temperature was also reported in [28]. Similarly, the conductivity of pollution layer increases with increase in surface temperature [18]. In this section, experiments were carried out at four different temperatures (5, 10, 15 and 20 °C). Each polluted sample was placed in a climate chamber at a specific value of temperature for 100 h before performing the tests. This time was allowed so that a steady-state value of surface hydrophobicity was obtained. Relative humidity and fog rate was kept constant inside the chamber. Figure 8 shows the measured values of surface resistance at different temperatures. It can be seen from experimental results that ambient temperature has very little effect on surface resistance. A decrease in surface resistance was observed with increase in temperature which might be due to the increased in surface conductivity of pollution layer [18]. This change in surface resistance with ambient temperature may be different at high temperatures, but due to the limitation of climate chamber, higher temperatures could not be tested.

6.5 Influence of dry band location

Pollution deposition on the surface of outdoor insulators is dependent on many factors and may not be uniform. The

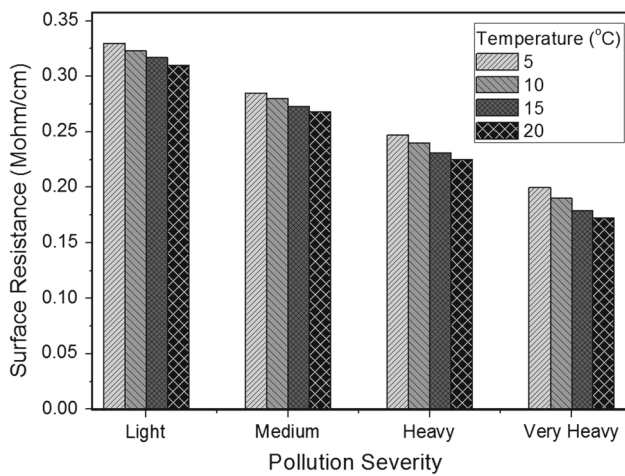


Fig. 8 Variation in surface resistance with ambient temperature: uniform pollution distribution, NSDD = 0.75 mg/cm^2 , moderate humidity, standard deviation = 1.8–3.3%

non-uniform pollution deposition on insulator surface leads to non-uniform current density and electric field distribution. Formation of clean and dry bands on the surface of silicone rubber outdoor insulators is very likely due to their hydrophobic nature. These clean and dry bands lead to high surface resistance and low leakage currents but at the same time to partial arcs and, under certain conditions, to flashover. The voltage distribution in the case of clean and dry bands is highly non-uniform, and most of the voltage drop occurs at the dry bands [29–31]. The presence of clean and dry zones on an insulator surface leads to higher surface resistance and flashover voltages. For a continuous pollution layer, the surface resistance follows Ohm's law and can be measured easily from the calculated values of voltages and currents. In the case of dry bands, the flow of leakage current is not uniform leading to non-uniform electric field distribution. In this section, tests were carried out on three different samples having dry bands at high-voltage end, middle part and ground end. Fog rate, relative humidity, ambient temperature and NSDD were kept constant, while volume conductivity was varied in all tests. Clean bands of 1 cm were created artificially during pollution application and were masked using acrylic glass during wetting process to keep them dry. The masking was removed once the wetting process was complete and before energization. Surface resistance was high as compared to uniform pollution at the start of the test, but it decreased as the surface wetting increased. Furthermore, surface resistance for the middle dry band was higher as compared to the other two cases. This could be due to the high impedance of middle dry band as compared to high-voltage and ground end dry bands. These results are in good agreement with the flashover results presented in [32,33]. Figure 9 shows the surface resistance in all three cases.

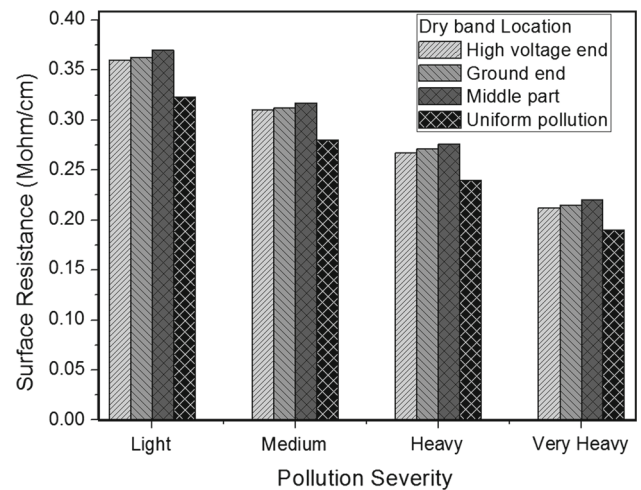


Fig. 9 Variation in surface resistance with dry band location: NSDD = 0.75 mg/cm^2 , moderate humidity, temperature = 10°C , standard deviation = 3.1–5.6%

6.6 Influence of dry band width

The presence of clean and dry bands on the insulator surface is influenced by many factors. Predicting the exact width and location of dry bands is a very complex task. Efforts have been made in the past to calculate the width of dry bands [32]. The previous literature [29,33] suggests that width of dry band effects the critical flashover voltage and arc propagation. In this section, experiments were carried out to study the influence of dry band width on surface resistance of silicone rubber sheets. Clean and dry bands of 0.5, 1.0, 1.5 and 2.0 cm were created at the high-voltage end of the samples, and tests were carried out under constant humidity, temperature and fog rate. Increase in surface resistance with increase in dry band width was observed as shown in Fig. 10. This may be due to the high resistance of a clean band as compared to a polluted one and the dependence of clean band resistance on its width. Furthermore, as the dry band width increases, the voltage required to establish a partial arc along the dry band increases resulting a decrease in leakage current and increase in surface resistance.

6.7 Influence of multiple dry bands

As mentioned earlier, dry band formation along the insulator surface is dependent on many factors. Predicting the exact number of dry bands along the insulator surface is a very complex task. It is reported in the literature that the possibility of dry band formation is high near the electrode ends due to the high electric field intensity resulting in corona and partial arcs at these locations [32,34–36]. Our previous experiments revealed that dry band can also form at the middle of insulator surface due to non-uniform pollution distribution [33]. In

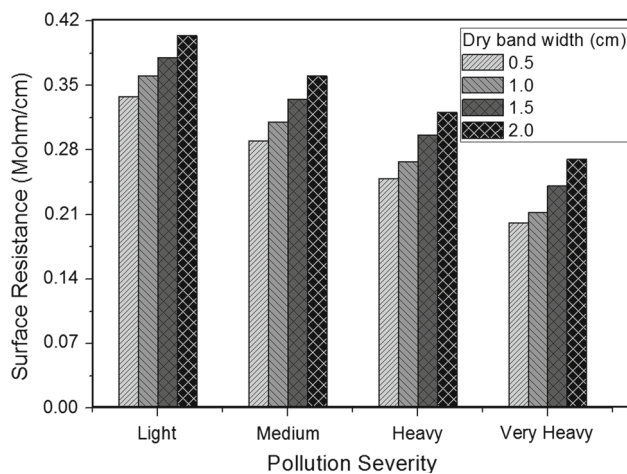


Fig. 10 Variation in surface resistance with dry band width: NSDD = 0.75 mg/cm^2 , moderate humidity, temperature = 10°C , standard deviation = 2.6–4.2%

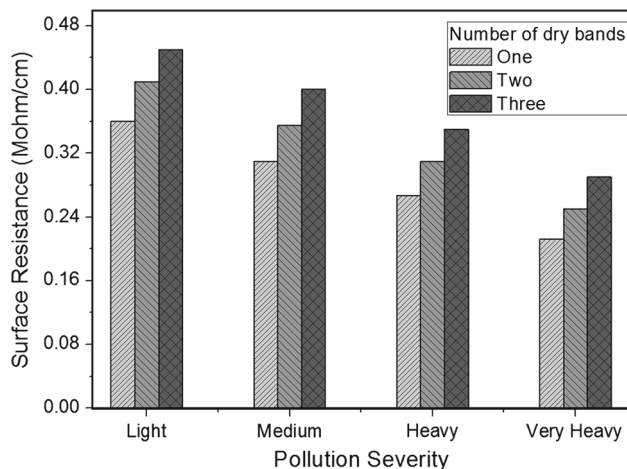


Fig. 11 Variation in surface resistance with number of dry bands: NSDD = 0.75 mg/cm^2 , moderate humidity, temperature = 10°C , standard deviation = 2.3–4.9%

this section, tests were carried out on samples having two and three dry bands (Fig. 2e, f). Volume conductivity of the pollution suspension was varied to model light, medium, heavy and very heavy pollution, while NSDD was kept constant at 0.75 mg/cm^2 . Increase in surface resistance with increase in the number of dry bands was observed. This could be due to the higher resistance of clean bands as compared to polluted bands. The flow of leakage current is interrupted by the presence of dry bands along the insulator surface leading to higher surface resistance. Figure 11 shows the relationship between the number of dry bands and surface resistance at different pollution severity levels.

7 Discussions

Decrease in flashover voltage of outdoor insulators with increase in pollution severity is a well-known fact and has been investigated by many researchers in the past. Mathematical models have been developed to predict flashover voltage under contaminated conditions for porcelain and glass insulators. The hydrophobic nature of silicone rubber insulators limits the applications of existing mathematical models. The ESDD on the surface of a silicone rubber may not be uniform, leading to inaccurate results. Surface resistance measurement is considered a reliable solution for predicting pollution severity and ageing of silicone rubber insulators. A decrease in surface resistance with increase in pollution severity was observed for uniformly polluted silicone rubber sheets (Fig. 5). In the case of very heavy pollution, surface resistance was $0.19 \text{ M}\Omega/\text{cm}$ which is higher than the critical surface resistance reported in [15]. This shows that new silicone rubber can resist flashovers even in very heavily polluted environments. However, the value of surface resistance is very close to the critical surface resistance and any decrease in surface hydrophobicity may lead to flashover.

Measuring NSDD of an in-service insulator is a difficult and time-consuming process. Previous studies have shown that with increase in inert content in pollution, the thickness and uniformity of water film increases in the insulator surface. These findings suggest that laboratory measurement of surface resistance at different levels of inert pollution content can be used for measuring the influence of inert material (NSDD) on flashover voltages of insulators. The traditional NSDD measurement for silicone rubber insulators can lead to misleading results because the silicone rubber reacts with the pollution material. A decrease in surface resistance with increase in NSDD was observed (Fig. 6). This might be because of the decrease in surface hydrophobicity with increase in inert pollution content [3].

The influence of relative humidity on surface resistance was studied, and results are reported in Fig. 7. In the case of high humidity (80–100%) and very heavy pollution severity, surface resistance value is closer to the critical surface resistance and the possibility of flashover is very high. This might be due to the fact that with increase in humidity, the silicone rubber surface absorbs water molecule which results in increase in surface conductivity, a decrease in surface resistance and flashover [25]. This also results in change in surface permittivity which may change surface resistance and flashover voltage.

The influence of ambient temperature on surface resistance was studied in a climate chamber at four different temperatures (5, 10, 15 and 20°C) (Fig. 8). There was no significant change observed in the surface resistance with change in temperature (in the given range). Although temperature affects the surface hydrophobicity of silicone rubber

but due to the limitation of climate chamber, we were unable to perform the tests at higher temperatures.

Dry band formation and their influence on flashover performance of silicone rubber insulators have been investigated in our previous work [19, 25]. The presence of a clean and dry band on the insulator surface leads to an increase in surface resistance (Fig. 9). This increase in surface resistance was more important for the middle dry band as compared to the high-voltage and ground dry bands (Fig. 9). The width of the dry band along the insulator surface varies and depends on various factors. Dry band width was varied from 0.5 to 2.0 cm in steps of 0.5 cm, and surface resistance was calculated. As expected, surface resistance increased with increase in dry band width. This might be because of the increase in residual resistance as clean band width increases [37]. A similar result was observed for multiple dry bands.

Surface resistance was found to be effected by pollution severity, NSDD, relative humidity and dry band formation. The increase in NSDD leads to a more uniform pollution layer and minimizes the surface resistance. A similar behaviour was observed when relative humidity was changed from low to moderate and moderate to high. Standard deviation varied from 1.8 to 5.6% in all tests, which might be due to the change in fog rate, humidity, temperature and uniformity of the pollution layer [25].

8 Conclusion

Flashover of outdoor insulators is a complex process and is dependent on various parameters (pollution, temperature, humidity, rain, fog, wind, dry bands, etc.). Due to the hydrophobic nature of silicone rubber insulators, the pollution constituents interact with the silicone fluid limiting the use of ESDD as standard for measuring pollution severity. Furthermore, surface ageing cannot be predicted by using ESDD. Surface resistance can be used to predict the surface contamination and ageing of silicone rubber insulators more accurately under polluted conditions. In this paper, surface resistance of silicone rubber sheets was measured under contaminated and dry band conditions. The following points were concluded from the experiments:

- With increase in pollution severity (pollution layer conductivity), surface resistance decreases
- Increase in the amount of non-soluble constituents (Kaolin in this case) leads to a decrease in surface resistance.
- Humidity inside the chamber affects the value of surface resistance, and as humidity increases from low to moderate and from moderate to high, surface resistance decreases.

- There is a very little influence of temperature (5–20 °C, in this range specifically) on surface resistance.
- Dry band formation along the insulator surface increases surface resistance.
- Increase in surface resistance caused by dry band formation is higher for the middle dry band as compared to the ground end and high-voltage end dry bands
- With increase in the width of dry band, surface resistance increases.
- Multiple dry bands along the insulator surface increase surface resistance.

The results presented are intended to develop intelligent systems which could be used to predict flashover voltage, contamination severity and ageing of silicone rubber insulators. One of the proposed future extension of current work is to develop random neural network model and predict the surface resistance under different polluted and dry band conditions. Furthermore, these results could be used to develop portable devices which enable utility engineers to measure surface resistance of outdoor insulators on site. It may also be helpful for asset managers in taking crucial decisions, e.g. changing or cleaning of insulators after a certain surface resistance value is reached.

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